Agricultural and Forest Meteorology 259 (2018) 240–249

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Asymmetric effects of daytime and nighttime warming on spring phenology in the temperate grasslands of China

Xiangjin Shen[a,⁎], Binhui Liu[b], Mark Henderson[c], Lei Wang[a], Zhengfang Wu[d], Haitao Wu[a], Ming Jiang[a], Xianguo Lu[a,⁎]

[a] Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130102, China
[b] College of Forestry, Northeast Forestry University, Harbin 150040, China
[c] Public Policy Program and Environmental Studies Program, Mills College, Oakland, CA 94613, USA
[d] School of Geographical Sciences, Northeast Normal University, Changchun 130024, China

ARTICLE INFO

Keywords:
Spring phenology
Start of growing season
NDVI
Climate change
Temperate grasslands
China

ABSTRACT

Understanding the spring phenology of temperate grasslands and its response to climate change are crucial for diagnosing the responses of ecosystem to regional climate change and projecting regional ecosystem carbon exchange. Using NDVI data from 1982 to 2015, this study investigated the changes of the start date of the vegetation growing season (SOS) for the temperate grasslands of China, and explored the possible effects of average monthly T_{max}, T_{min} and total precipitation on the SOS across different grassland vegetation types. We improved on prior studies of climate change in China's temperate zone by focusing only on grasslands unchanged over this extended study period. The results showed that the SOS significantly advanced at a rate of 1.84 days/decade from 1982 to 2015, controlled mainly by spring precipitation and spring and winter temperatures, with differing degrees of influence among vegetation types. On average, an increase of 10 mm in spring precipitation would advance SOS by 1.7 days across the temperate grasslands of China. Although warmer temperatures generally led to advanced SOS, this study revealed for the first time that the seasonal effects of daytime and nighttime warming on the SOS of temperate grasslands in China were asymmetric, with T_{max} more influential in winter and T_{min} more influential in spring. An increase of 1 °C in winter T_{max} and spring T_{min} would advance SOS by 0.42 and 1.34 days, respectively, compared with effects of 0.24 or 0.64 days for 1 °C increases in winter T_{min} or spring T_{max}. Given the global asymmetry in daytime and nighttime warming, this study highlights the asymmetric effects of daytime and nighttime warming on the SOS of temperate grasslands in China, and suggests that the impacts of seasonal T_{max} and T_{min} should be considered separately in the SOS modules of terrestrial ecosystem models for temperate grasslands.

1. Introduction

Spring phenology is an important indicator of vegetation dynamics and plays an important role in vegetation activity and ecosystem functions (Zhang et al., 2004; Piao et al., 2007; Richardson et al., 2009; Cong et al., 2013; Melaas et al., 2013; Liu et al., 2016b; Wu et al., 2016; Donnelly et al., 2017; Liu et al., 2017). The start date of the vegetation growing season in spring (start of season, or SOS) has been determined from satellite data in recent years (Liang et al., 2011, 2014; Shen et al., 2011; Zeng et al., 2011; Cong et al., 2012, 2013; Garonna et al., 2014; Karlsen et al., 2014; Liu et al., 2014; Zhou et al., 2014; Fu et al., 2015b; Piao et al., 2015; Shen et al., 2015a; Zhang et al., 2015; Liu et al., 2016a; Shen et al., 2016a; Verger et al., 2016; Wu et al., 2016; Vrieling et al., 2017). Variations in the SOS can have some effects on the carbon cycle of terrestrial ecosystems, and can alter land surface energy (Donnelly et al., 2011; Richardson et al., 2013; Shen et al., 2015b; Yang et al., 2017). The SOS is very sensitive to climate change, and an understanding of changes of the SOS in response to climate is crucial for assessing the responses of ecosystem to climate change and predicting future ecosystem dynamic (Badeck et al., 2004; Piao et al., 2006a, b; Körner and Basler, 2010; Zeng et al., 2011). In temperate regions, the SOS of vegetation is significantly controlled by climate factors such as temperature and precipitation (Piao et al., 2006a, b; Cong et al., 2012). However, these relationships between the SOS and climate could vary significantly across different areas and vegetation types (Donnelly et al., 2006, 2015; Cong et al., 2012; Zhou et al., 2014; Ding et al., 2015, 2016; Liu et al., 2016a). China's temperate grasslands constitute the third largest grassland area in the world (Lee et al., 2002) and have

⁎ Corresponding authors at: 4888 Shengbei Street, Changchun, 130102, Jilin, China.
E-mail addresses: shenxiangjin@iga.ac.cn (X. Shen), luxg@iga.ac.cn (X. Lu).

https://doi.org/10.1016/j.agrformet.2018.05.006
Received 7 January 2018; Received in revised form 5 May 2018; Accepted 8 May 2018
Available online 15 May 2018
0168-1923/

experienced dramatic climatic change over the past several decades (Shen et al., 2017), significantly affecting the spring phenology. Many studies have investigated the impacts of temperature and precipitation on SOS across the temperate grasslands of China (Piao et al., 2006a, b; Cong et al., 2013; Wu et al., 2016), but prior studies did not compare changes in the SOS across different grassland vegetation types. In recent years, many studies have found different responses of SOS to climate change in different grassland ecoregions of the Tibetan Plateau (e.g. Liu et al., 2014, 2016a, b; Ding et al., 2015, 2016; Wang et al., 2015; Zhang et al., 2015; Zhu et al., 2017). Considering the relationships between the SOS and climate could vary across different vegetation types, the possible effects of climate on the SOS across different temperate grassland vegetation types in China should be further investigated.

A recent study found that increasing daytime maximum temperature (T_{max}) has had a greater impact on the SOS than has increasing night-time minimum temperature (T_{min}) in the Northern Hemisphere (Piao et al., 2015). It receives great attention because that T_{min} increased faster than T_{max}, resulting in a decreasing diurnal temperature range, during the past decades in most parts of the world (IPCC, 2013). In some regions, future climate change might increase the diurnal temperature range (Shen et al., 2014a), which also has complex effects on the phenology. Piao et al., (2015) speculated that daytime T_{max} rather than nighttime T_{min} might fulfill more efficiently the accumulation of heat needed to unfold leaves, and would be more responsible for plant carbon fixation and thus the onset of green-up since plant photosynthesis only occur during the daytime. On the Tibetan Plateau, however, Shen et al (2016a) found that changes in the SOS were more strongly associated with warming winter T_{min}, rather than T_{max}. This may be because higher T_{min} could alleviate frost damage, but higher T_{max} could exacerbate drought effects over the cold and dry areas (Yu et al., 2010; Shen et al., 2016a). Compared with the cold and dry Tibetan Plateau, the temperate grassland region of China is warmer, with a drier, arid and semi-arid climate. To understand the mechanisms by which temperatures influence the spring phenology of vegetation, it is crucial to investigate the separate impacts of daytime and nighttime warming on the SOS across the temperate grasslands of China. In addition, considering the possible different effects of seasonal temperature on spring phenology (Yu et al., 2010; 2012), the seasonal response of SOS to daytime and night-time warming should also be considered.

In this study, we investigated changes in the SOS across the temperate grasslands of China, detected using normalized difference vegetation index (NDVI) derived from AVHRR satellite imagery from 1982 to 2015. We explored the possible effects of average monthly temperatures (including T_{mean}, T_{max} and T_{min}) and total precipitation on the SOS across different grassland vegetation types. Different from previous studies, this study only analyzed the unchanged (belonging to the same land use type) temperate grasslands during the study period in order to minimize the possible impacts of land-use change on SOS results. The findings of this study can aid in diagnosing the responses of ecosystems to regional climate change and further understanding global climate change.

2. Materials and methods

2.1. Study area

According to the Vegetation Atlas of China (Chinese Academy of Sciences, 2001), China's temperate grasslands are mainly distributed across the Inner Mongolian Plateau, the Songliao Plain and the Loess Plateau (Fig. 1). The elevation of this temperate grassland zone of China ranges from 60 to 4441 m, which is generally lower from west to east. China's temperate grasslands occur in a region with a semi-arid to arid climate. Annual average temperatures in this region vary from −5 °C to 10 °C, and annual precipitation ranges from 35 to 530 mm (Shen et al., 2017). It is reported that annual mean temperature showed a significant increase in China including the temperate grassland region of China from 1980 to 2015 (Shen et al., 2018). Over the whole study area of the temperate grassland region in China, annual T_{max} and T_{min} significantly ($P < 0.01$) increased by 0.31 °C/decade and 0.35 °C/decade, respectively, during 1982–2015. Temperate grasslands in this region include three different vegetation types of temperate meadow, temperate steppe, and temperate desert steppe, which are classified in raster land use/cover products of China used in this study.

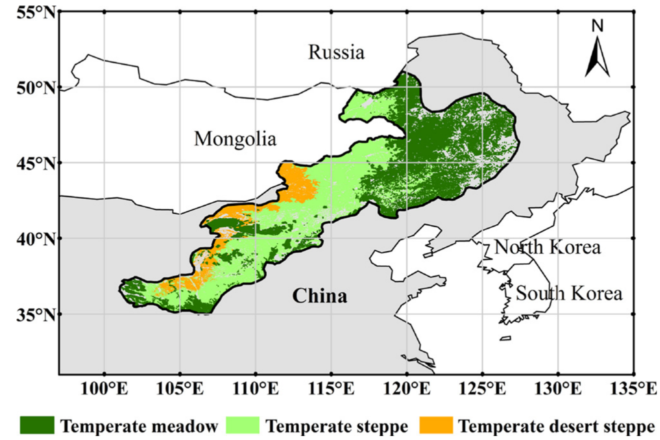

Fig. 1. The spatial distribution of grassland vegetation types (unchanged from the 1980s to 2015) in the temperate grassland zone of China.

2.2. Datasets and determination of SOS

For this study, we analyzed vegetation phenology evident in data from the Global Inventory Monitoring and Modeling Studies (GIMMS), specifically the GIMMS-3 G version 1 NDVI dataset derived from Advanced Very High Resolution Radiometer (AVHRR) satellite imagery. The dataset spans 1982 through 2015 with a 15-day temporal resolution and an 8 km × 8 km spatial resolution (Tucker et al., 2005, Wang et al., 2017a, b). The GIMMS-3 g NDVI data, processed to minimize errors and biases, have been widely used for investigating long-term changes in vegetation around the globe (e.g. Piao et al., 2006a, b; Cong et al., 2013; Wu and Liu, 2013; Yang et al., 2015; Wang et al., 2017a, b). We also made use of land use and land cover (LULC) maps for two periods (the 1980s and 2015) to detect changes in vegetation types within the study area. The LULC data had a spatial resolution of 100 m × 100 m, and were obtained from the National Earth System Science Data Sharing Platform of China (Shen et al., 2016b). These land use maps were classified into six first levels of land use categories and twenty-five second levels including three grassland vegetation types of temperate meadow, temperate steppe, and temperate desert steppe (Shen et al., 2016b). Gridded meteorological data including monthly mean (T_{mean}), maximum (T_{max}) and minimum (T_{min}) temperature and precipitation from 1981 to 2015, with spatial resolution of 0.5° × 0.5°, were generated from more than 800 meteorological stations throughout China (Yang et al., 2015) based on Kriging interpolation technique (Goovaerts, 1997). In this study, the land use map and climate data were resampled to a spatial resolution of 8 km × 8 km in accordance with the NDVI data.

2.3. Analyses

In this study, the Polyfit-Maximum method was used to identify the starting date of vegetation growing season (SOS). The Polyfit-Maximum method treats the period of largest increase of the seasonal NDVI time series as the onset of vegetation growth, and it has been widely used in determining the starting date of vegetation green-up (e.g. Piao et al., 2006a, b; Cong et al., 2012, 2013; Fu et al., 2014a; Wang et al., 2017a, b). For each pixel, the relative change in NDVI is calculated from annual

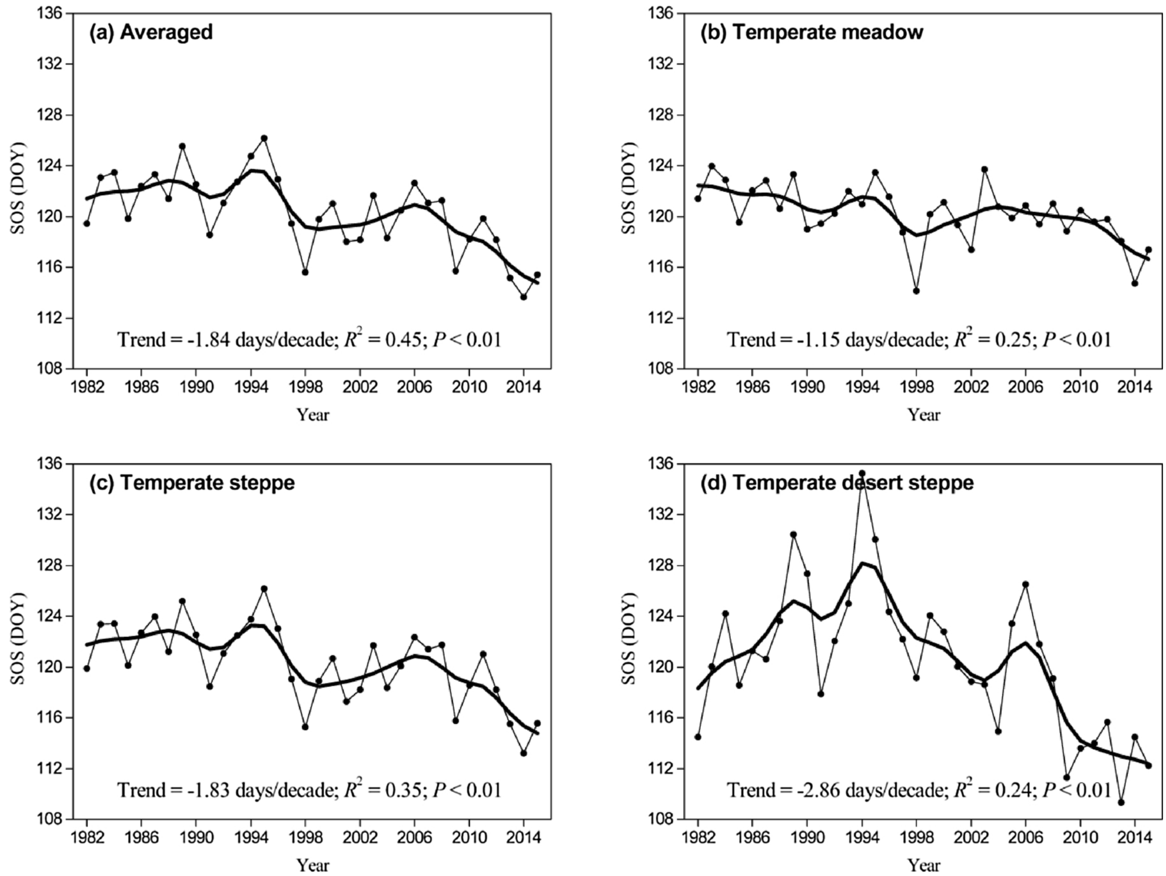

Fig. 2. Trends and temporal variations of the start of the growing season (SOS) in temperate grasslands of China during.1982–2015.

NDVI curves at 15-day intervals, using Eqn.1.

$$NDVI_{ratio}(t) = \frac{NDVI(t+1) - NDVI(t)}{NDVI(t)} \quad (1)$$

where $NDVI_{ratio}$ is the relative change in NDVI, and t is the day of year (DOY). We then detected the maximum $NDVI_{ratio}$ at time t, and used the corresponding threshold NDVI(t) to determine the onset dates of green-up from the time-series of NDVI data, filtered by an inverted 6-degree polynomial function (Piao et al., 2006a, b; Cong et al., 2012), as shown in Eq. (2), where a_1, a_2, a_3.. . a_6 are the fitted coefficients obtained from the least square regression:

$$NDVI(t) = a + a_1t^1 + a_2t^2 + a_3t^3 + a_4t^4 + a_5t^5 + a_6t^6 \quad (2)$$

To exclude the effects of land-use change on our results, we extracted unchanged pixels classified as belonging to the same land use type in LULC maps for the 1980s and 2015, following the procedures described in previous studies (Shen et al., 2016a). The averaged values of each variable for each grassland type were calculated from the averages of all pixels belonging to the same vegetation type at both points in time.

We used a linear least-squares regression to calculate the temporal trends in the SOS from 1982 through 2015. In this study, the cumulative sum (CUSUM) test and bootstrap analysis (Fischer et al., 2011; Shen et al., 2018) were adopted to get the change point in the time series of the SOS. To explore the influences of temperature and precipitation on the SOS, we used a partial least-squares (PLS) regression (Wold, 1995; Wold et al., 2001); PLS regression is widely used in establishing the correlations between the independent and dependent variables, and it has been shown to work well even when the number of observations is obviously smaller than the number of independent variables (Luedeling et al., 2013). Compared with conventional regression approaches, PLS regression avoids the problem of autocorrelation between independent variables, such as the climatic factors of the individual months (Yu et al., 2010). In this study, a model coefficient and a Variable-Importance-in-the-Projection (VIP) value are calculated for each independent variable. According to previous studies, variables with VIP equal or greater than 0.8 are considered important for the model in current study (Wold, 1995; Yu et al., 2010). Furthermore, we calculated the sensitivity of the SOS to temperature and precipitation, defined as the change in the SOS date per unit change of temperature and precipitation (Fu et al., 2015b; Shen et al., 2015a), for further exploring the impacts of climate change on the SOS in the temperate grasslands of China. The sensitivity of SOS to temperature (or precipitation) was the coefficients of temperature (or precipitation) using the multiple linear regression in which climatic parameter was set the independent and SOS the dependent variable for each pixel.

3. Results

3.1. Trends and temporal variations of spring phenology

During the study period of 1982–2015, the starting date of vegetation growing season (SOS) across the temperate grasslands of China occurred between 114 and 126 DOY (with 120 DOY corresponding to April 30, or April 29 in leap years) (Fig. 2a). On average, the SOS occurred on 120 DOY in the temperate meadow and temperate steppe, and on 121 DOY in the temperate desert steppe. In general, the SOS for temperate meadow varied from 114 through 124 DOY (Fig. 2 b), and between 113 and 126 DOY for temperate steppe; temperate desert steppe showed a wider range, with the SOS ranging from 109 to 135 DOY (Fig. 2d).

To investigate the variations in spring phenology, we calculated the trends in mean SOS across the study area and for the three grassland vegetation types. Our results showed that the mean SOS over the entire

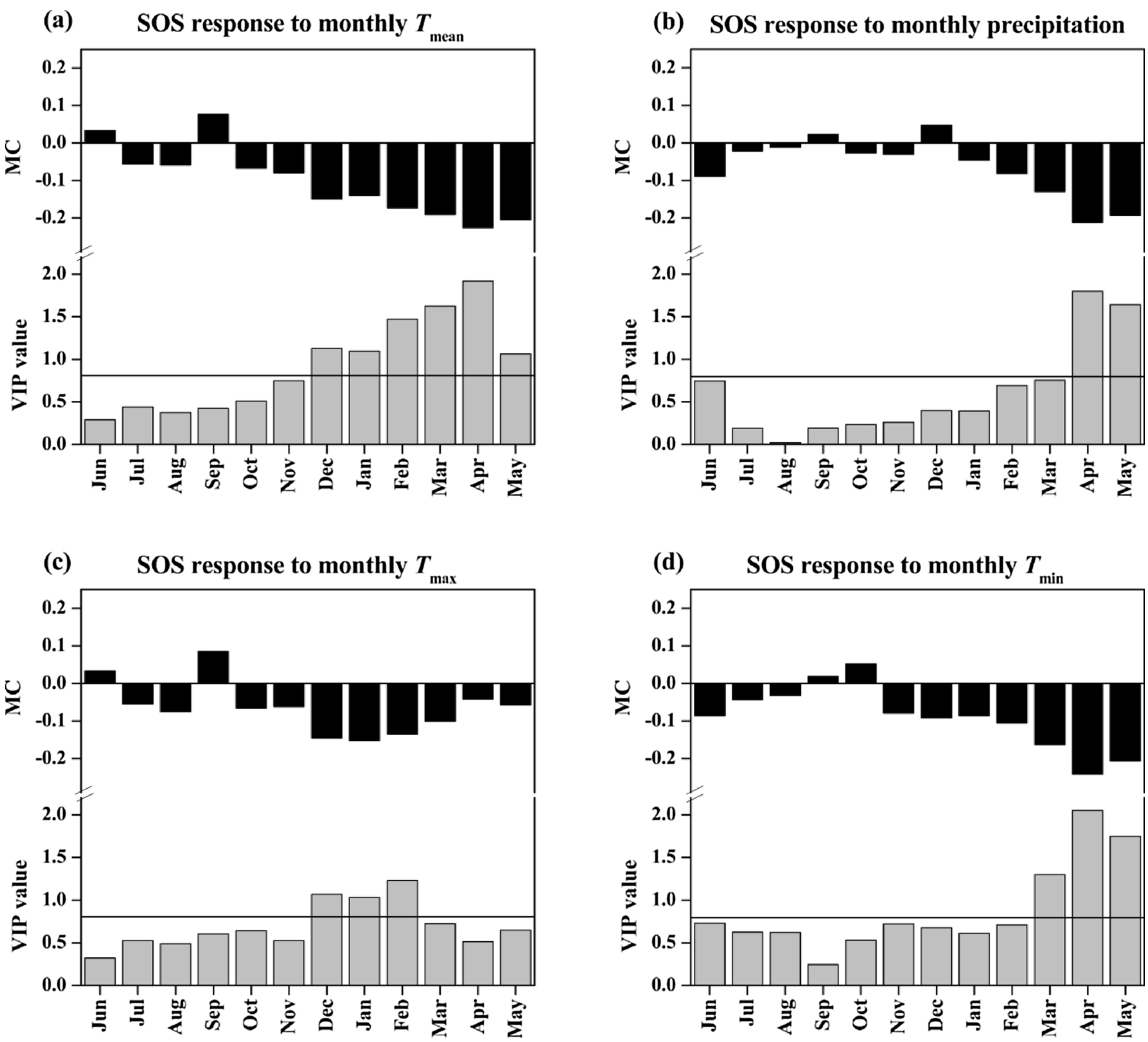

Fig. 3. Responses of the start date of the vegetation growing season (SOS) in China's temperate grasslands to average monthly temperatures and total precipitation according to partial least-squares (PLS) regression (1982–2015). Model coefficients (MC) and the variable importance plots (VIP) values reflect the degree and the significance of the impact of climatic factors on the SOS, respectively.

study area significantly advanced at a rate of 1.84 ± 0.31 days/decade (P = 0.000) from 1982 through 2015. Over the 34-year study period, all three grassland vegetation types exhibited earlier green-up: the SOS significantly advanced by 1.15 ± 0.23 days/decade (P = 0.002) for temperate meadow, 1.83 ± 0.32 days/decade (P = 0.000) for temperate steppe, and 2.86 ± 0.75 days/decade (P = 0.003) for temperate desert steppe.

Within the study period, the regional average SOS fluctuated until 1994, significantly advanced (i.e., earlier green-up) from 1995 to 1998, showed a weak receding trend (i.e., later green-up) from 1999 to 2006, and then significantly advanced after 2006 (Fig. 2a). The temporal profile of SOS change for the temporal steppe vegetation type reflected the same overall pattern (Fig. 2c), but the temperate meadow and temperate desert steppe displayed different patterns. For temperate meadow, the average SOS fluctuated but generally advanced from 1982 to 1998, receded from 1999 to 2004, and thereafter showed a rapid advance, especially after 2011 (Fig. 2b). For temperate desert steppe, the average SOS at first showed a significant receding trend from 1982 to 1994, but then showed a significant advance from 1995 through 2015 (Fig. 2d).

3.2. Relationships between SOS and climatic factors

Fig. 3 illustrates the response of the SOS in China's temperate grasslands to average monthly temperatures and total precipitation, as calculated by PLS regression. The PLS regression analysis included monthly mean temperature (T_{mean}), maximum temperature (T_{max}), minimum temperature (T_{min}), and precipitation as important variables into an explanatory model for the SOS.

. The VIP results suggest that temperatures between December and May, and precipitation in April and May contributed to the change of the SOS in the temperate grasslands of China (VIP values above 0.8) (Fig. 3). Model coefficients (MC) were negative in these months, indicating that warm temperatures and increasing precipitation contributed to an advance in the SOS date. Although warm temperatures in the winter (December through February) and spring (March to May) advanced the start of the growing season, the values of VIP and MC showed that there were asymmetric effects of daytime and nighttime warming on SOS in these two seasons. The SOS was more strongly associated with T_{max} (with higher absolute MC values and higher VIP scores) than with T_{min} during winter, but was more strongly associated with T_{min} than T_{max} in spring. This finding was confirmed by the response of SOS to monthly diurnal temperature range in the PLS regression (Fig. 4). Model coefficients for diurnal temperature range in winter were negative, indicating that T_{max} had a stronger impact on SOS than T_{min} during winter. By contrast, the model coefficients for the diurnal temperature range in spring were positive, suggesting that T_{min} played a more important role affecting SOS than did T_{max} in the spring.

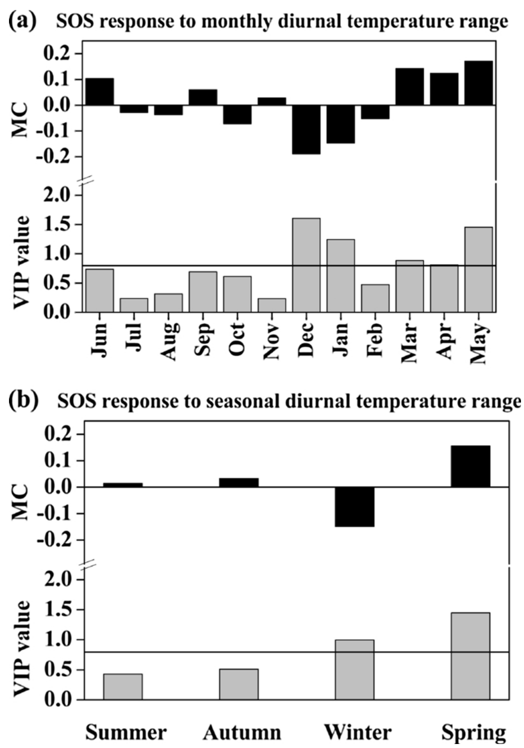

Fig. 4. Response of the start date of the vegetation growing season (SOS) in temperate grasslands of China between 1982 and 2015 to monthly diurnal temperature range according to partial least-squares (PLS) regression. Model coefficients (MC) and the variable importance plots (VIP) values reflect the degree and the significance of the impact of climatic factors on the SOS, respectively.

Although the model coefficients for the diurnal temperature range in summer and autumn were also positive, the values of MC and VIP were relative small (Fig. 4b). According to the PLS regression (Wold, 1995; Wold et al., 2001), the low VIP values (VIP value < 0.8) in summer and autumn (Fig. 4b) suggest that there are no significant differences between the possible effects of T_{max} and T_{min} on the SOS in both two seasons.

For all three grassland vegetation types, warm temperatures in the winter and spring advanced the spring SOS (Fig. 5). Similar asymmetric effects of daytime and nighttime warming on the SOS were evident for each vegetation type, with the SOS more strongly influenced by daytime temperature (T_{max}) in the winter, and by nighttime temperature (T_{min}) in the spring. For temperate desert steppe, the MC values between SOS and T_{max} were positive for March, April, and May (Fig. 5g), indicating that warm daytime temperatures in spring may have a delaying effect on SOS for that vegetation type. Although the MC values between SOS and T_{max} were also positive in July, August and November, the small corresponding VIP values (VIP value < 0.8), indicate no significant effects of T_{max} on the SOS in these three months. In terms of the response of SOS to monthly precipitation, the MC and VIP results indicate that the positive or negative impact of precipitation is significant (VIP value ≥ 0.8) when the absolute MC value approaches or exceeds 0.18. From the results, we found that increases in precipitation in April and May contributed to advancing SOS for all three vegetation types, and increases in March precipitation also had that effect in the temperate desert steppe (Fig. 5 c, f, i). For the temperate desert steppe, although February precipitation seems to have the same response as March, both the absolute values of MC (0.12) and VIP (0.68) for precipitation in February were smaller than that in March (0.21 and 0.86, respectively) (Fig. 5i). It suggests that precipitation in February had no significant effect on the SOS of the temperate desert steppe.

3.3. Sensitivity of SOS to temperature and precipitation

To further explore the impacts of climate change on the SOS in the temperate grasslands of China, we calculated the sensitivity of the SOS trends to temperature and precipitation using multiple linear regressions. The sensitivity of SOS to climate change was the coefficients of temperature (or precipitation) using the multiple linear regressions in which temperature (or precipitation) parameter was set the independent and SOS the dependent variable. The results showed that the sensitivity of the SOS to average monthly temperature and total precipitation was negative over the temperate grasslands of China, with high temperature sensitivity between December and May, and high precipitation sensitivity during spring (Fig. 6). On average, the SOS would advance by about 0.17 days in response to each 1 mm increase of spring precipitation. A 1 °C warming in winter T_{mean} advanced the SOS date by 0.53 days, whereas the same increase in spring T_{mean} corresponded to an SOS advance of 1.25 days. Although warming in winter and spring usually contributed to an early SOS, the SOS responded more strongly to daytime warming in winter and to nighttime warming in spring (Fig. 6a). For the entire study area, an increase of 1 °C in winter T_{max} and spring T_{min} would advance SOS by 0.42 and 1.34 days, respectively (Fig. 7). By contrast, the SOS only advanced by about 0.24 and 0.64 day in response to 1 °C warming of winter T_{min} and spring T_{max}.

For the three vegetation types, change in the SOS was also closely correlated with winter T_{max}, spring T_{min}, and spring precipitation. The sensitivity of the SOS to spring T_{min} was similar among the different grassland vegetation types (ranging from 1.17 to 1.41 days /°C), but the sensitivity to winter T_{max} was notably different: an increase of 1 °C in winter T_{max} would advance the SOS by 0.46 day for temperate steppe, but only 0.24 day for temperate desert steppe (Fig. 7). The temperate desert steppe had the highest sensitivity to spring precipitation (-0.21 day/mm), and temperate meadow had the lowest precipitation sensitivity (-0.06 day/mm). To further explore the response of the SOS to spring precipitation, we calculated the sensitivity of SOS for each grid cell with a resolution of 8 km × 8 km. In general, the negative precipitation sensitivities were significant ($P < 0.05$) at spring precipitation below 70 mm (Fig. 8). The sensitivity of SOS to spring precipitation decreased with increasing precipitation in cells that reported less than 70 mm of spring precipitation, but became weak to neutral in cells with precipitation of 70 mm or above (Fig. 8).

4. Discussion

4.1. Trends and temporal variations of spring phenology

By using long-term satellite NDVI records and the Polyfit-Maximum method, this study estimated the starting dates of spring growing season (SOS) in the temperate grasslands of China from 1982 to 2015. The results showed that the SOS occurred between 114 and 126 DOY, which is roughly consistent with two previous studies (Piao et al., 2006a, b; Cong et al., 2013). The mean SOS of temperate grasslands in China occurred on April 30th, which is a little earlier than the early May dates reported by the earlier studies. This discrepancy may be attributed mainly to the differences in study area and the vegetation types examined: these two previous studies investigated the whole temperate zone of China (Piao et al., 2006a, b; Cong et al., 2013), including most of the Tibetan Plateau, the world's largest high-elevation region where the SOS was usually later than that in the temperate grassland region (Wu et al., 2016). In addition, it is reported that SOS in the Tibetan Plateau grasslands showed different responses to climate change at different elevations (Liu et al., 2014, 2016a,b). For example, spring phenology in the Tibetan Plateau grasslands showed a stronger response to variations of temperature at higher elevations than at lower elevations (Liu et al., 2014). Therefore, the change in species composition of meadow and steppe ecoregions along the elevational gradient

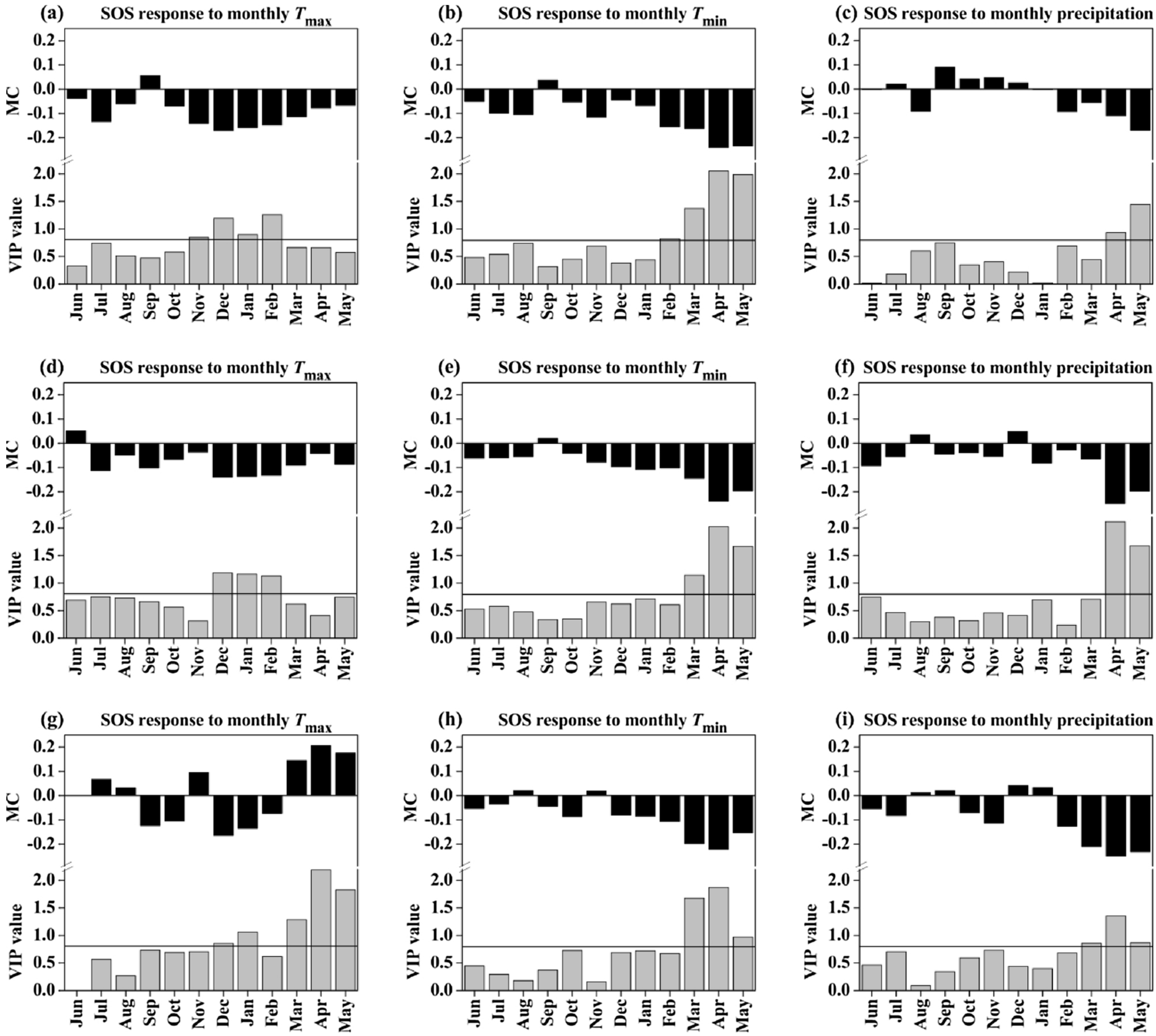

Fig. 5. Responses of the SOS for temperate meadow (a, b, c), temperate steppe (d, e, f), temperate desert steppe (g, h, i), between 1982 and 2015 to average monthly temperatures and total precipitation according to PLS regression. Model coefficients (MC) and the variable importance plots (VIP) values reflect the degree and the significance of the impact of climatic factors on the SOS, respectively.

may also contribute to the different SOS results. Another difference between our study and these previous studies is that the previous studies did not consider the possible impacts of land-use change on SOS results: in this study we only analyzed the unchanged temperate grasslands of China during the study period in order to minimize any such effects. Thus this may also explain some of the differences in timing of the current study with previous ones.

We found that the average SOS across China's temperate grasslands advanced by 1.84 days/decade from 1982 to 2015. This estimation is larger than the result (1.30 days per decade) of Cong et al. (2013), but smaller than the estimation (7.90 days per decade) from Piao et al. (2006a, b). Besides the differences in study area and vegetation types considered by these studies, the difference in study periods also contributes to the discrepancies among the reported trends of SOS. For example, if we compared the analysis results over the same period with previous study, we find that our trend of 1.29 days/decade during 1982–2010 is close to that reported by Cong et al. (2013). Among the different vegetation types, we found that the temperate desert steppe had the widest range of SOS from 1982 to 2015, varying from 109 to 135 DOY. This large variation in the SOS may be related to the greater sensitivity of vegetation to climate change in arid regions (Shen et al., 2015b, c). All three grassland vegetation types displayed earlier green-up. The largest advance in the SOS (2.86 days/decade) was found in temperate desert steppe, confirming that the green-up onset date of desert vegetation experienced the fastest advance in temperate China (Piao et al., 2006a, b). For the temperate grassland region of China, the changes of SOS in both meadow and steppe ecoregions were different from that reported in the cold Tibetan Plateau, although recent reports of SOS changes in the Tibetan Plateau grasslands showed varied results. The different growth environments of grasslands and different climate changes in these two arid/semi-arid regions mainly account for these differences. By using GIMMS NDVI data, some studies found an advanced SOS during the early 1980s to the mid-1990s or late-1990s, but the SOS significantly delayed during the first decade of this century (Yu et al., 2010; Piao et al., 2011). By merging GIMMS and SPOT NDVI product, however, Zhang et al. (2013) found that the SOS consistently advanced at a rate of 10.40 days/decade in the Tibetan Plateau from 1982 to 2011. Based on Tibetan Plateau tree-ring data, Yang et al. (2017) found that the SOS significantly advanced by 2.50 days/decade over the period 1982–2014. Although with different degrees of SOS

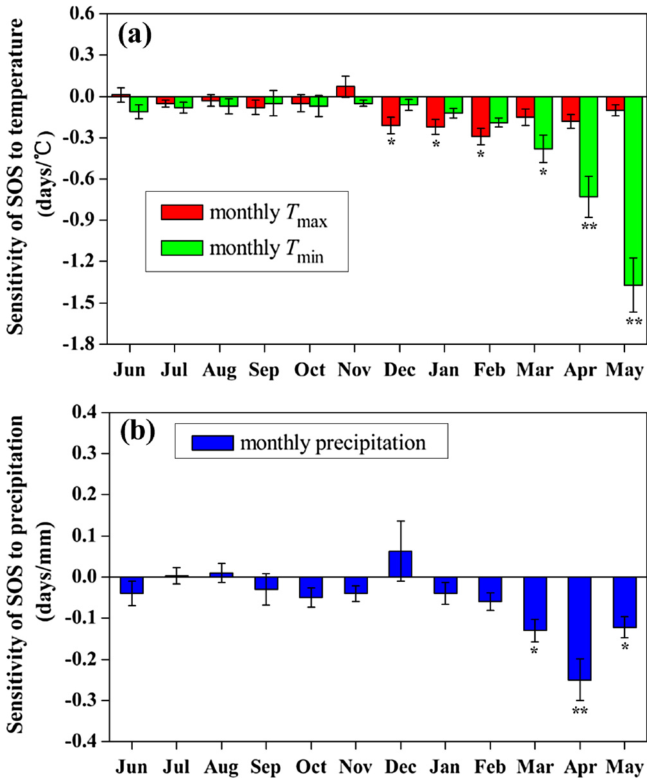

Fig. 6. Sensitivity of change in the start season (SOS) to average monthly temperature (d/°C) and total precipitation (d/mm) across the temperate grasslands of China. *and ** indicate significance at $P < 0.05$ and $P < 0.01$ levels, respectively.

changes in these two previous studies, the reported advancing rates of SOS in the Tibetan Plateau were larger than that of SOS in the study area of this study. In addition, there are also many studies that found no significant temporal trend in spring phenology over the Tibetan Plateau (Shen et al. 2014b; Chen et al. 2015). Although the NDVI data have been widely used in deriving land surface phenology, the applications of NDVI may be limited because of its saturation in high vegetation coverage area and its sensitivity to soil background (Carlson and Ripley 1997; Huete et al. 2002). It is reported that enhanced vegetation index has optimized vegetation signals, and the reconstructed daily two-band enhanced vegetation index (EVI2) time series considerably improved the estimates of land surface phenology (Cao et al., 2015; Zhang, 2015). Based on the time series of EVI2, Liu et al (2016a) found that SOS showed no significant trend from 1982 to 2013 in most of the Tibetan Plateau. The SOS significantly advanced in eastern meadow ecoregion, while it showed later trends in steppe ecoregion and southern meadow ecoregion (Liu et al., 2016a). These complex changes are generally supported by many recent field based observations (Zhou et al. 2014; Chen et al. 2015). Based on the observational data, Zhou et al., (2014) reported that the significant advance of SOS was only found in alpine meadow, confirming that the phenology in steppe ecoregion can differ from that in meadow ecoregion. Considering the uncertainties in remote-sensing estimates of land surface phenology, more phenological information from observations on the ground, as well as from more accurate vegetation index are still needed to verify the SOS results for the temperate grasslands of China in current study.

4.2. Relationships between SOS and climatic factors

Recent studies reported that spring phenology was more strongly and positively associated with T_{max}, rather than T_{min} in the Northern Hemisphere (Peng et al., 2013; Piao et al., 2015). Fu et al. (2016) found that the effect of daytime temperature on leaf unfolding phenology in temperate trees was about three times higher than that of nighttime temperature. On the Tibetan Plateau, however, Shen et al. (2016b) found that changes in the SOS were more strongly associated with warming winter T_{min}, rather than T_{max}. Different from all the previous studies, in the arid and semi-arid temperate grasslands of China, we revealed for the first time that the effects of T_{max} and T_{min} on the SOS of temperate grasslands in China were asymmetric in winter and spring: the SOS was more strongly associated with T_{max} rather than T_{min} in the winter, whereas the SOS showed a stronger correlation with T_{min} than with T_{max} in the spring. Given the asymmetry between daytime and nighttime warming at the global scale, these asymmetric effects of daytime and nighttime warming in winter and spring on SOS in temperate grasslands of China deserve further attention.

The VIP results showed that, besides temperatures between December and May, precipitation in April and May also contributed to the SOS change in the temperate grasslands of China (Fig. 3). It confirmed many studies that the SOS in the temperate grasslands of China was mainly controlled by spring temperature and precipitation (e.g., Piao et al., 2006a, b; Wu and Liu, 2013; Wu et al., 2016). In general, both warmer temperature and more precipitation during spring led to advancing SOS. Our results further showed that spring T_{min} exerted greater control over the vegetation green-up date than did spring T_{max}. Increases in spring T_{max} had a weak effect on advancing the SOS of the temperate meadow and temperate steppe vegetation types, and even

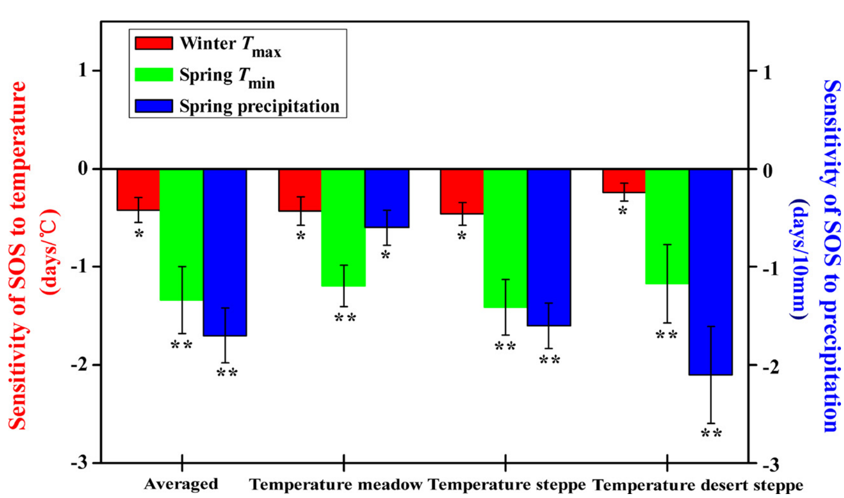

Fig. 7. Sensitivity of the SOS to seasonal temperature (days/°C) and precipitation (days/10 mm) across the study area and for the three grassland vegetation types. *and ** indicate significance at $P < 0.05$ and $P < 0.01$ levels, respectively.

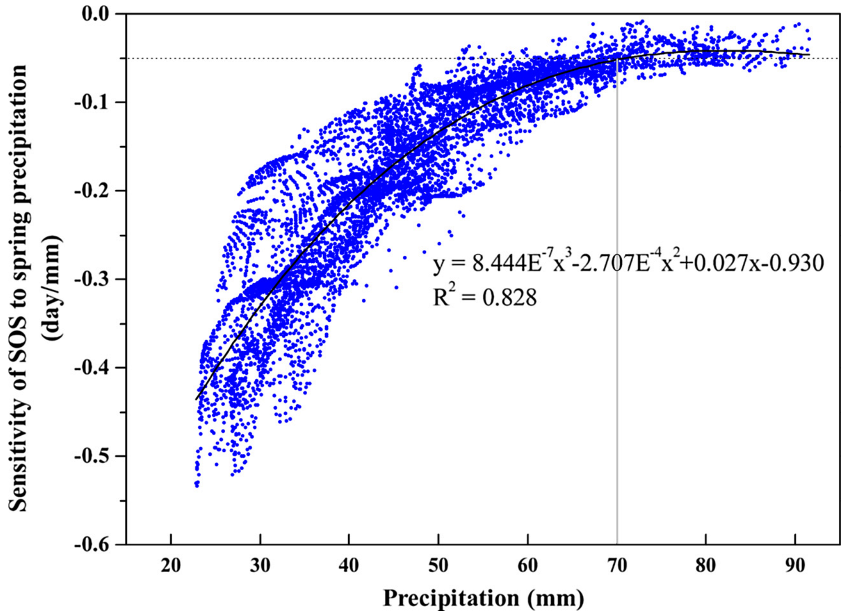

Fig. 8. Variations in the sensitivity of the SOS to spring precipitation along the spatial gradient of long-term average spring precipitation across the temperate grasslands of China. Precipitation sensitivities of approximately -0.05 (corresponding to 70 mm spring precipitation) are statistically significant at the 0.05 level.

had a delaying effect on the SOS for temperate desert steppe. The apparent stimulating impacts of increasing T_{min} were probably due to reduced frost damage (Piao et al., 2015), while the weak impacts of higher T_{max} on SOS might be related to the accompanying reduction in water availability (Shen et al., 2016a). By enhancing evaporation, increasing daytime temperature could exacerbate drought effects in dry areas, thereby delaying the onset of green-up for temperate desert steppe.

We also found that winter T_{max} accelerated the SOS for each vegetation type. Although the SOS over the temperate grasslands of China was mainly controlled by spring T_{max} and precipitation, high VIP scores (above 0.8 in the PLS regressions for each vegetation type) indicate that the role of winter T_{max} on SOS cannot be overlooked. In temperate regions that experience a cold winter, vegetation needs certain thermal conditions—cumulative temperature above some threshold—to begin its spring growth (Shen et al., 2011; Piao et al., 2015). Before the green-up of vegetation, T_{min} is more likely to be below the threshold temperature than is T_{max}, so it contributes less to achieve the thermal requirement for green-up (Piao et al., 2015). Therefore, winter T_{max} warming is more efficient than T_{min} warming for fulfilling the thermal requirement that triggers the SOS in the temperate grasslands of China. However, it is reported that the heat requirement for spring phenology have increased at northern middle and high latitudes (Fu et al., 2014b, 2015a). Considering the fact that increased heat requirement might overweight the daytime and nighttime temperature increase, the advancement of the SOS in the temperate grasslands of China might less than we expected.

4.3. Sensitivity of SOS to temperature and precipitation

The results of our temperature sensitivity analysis confirmed that winter T_{max} and spring Tmin played more important roles in affecting the SOS over the temperate grasslands of China. An increase of 1 °C in winter T_{max} and spring T_{min} would advance SOS by 0.42 and 1.34 days, respectively. The three grassland vegetation types displayed similar sensitivities of the SOS to spring T_{min}, but the sensitivity to winter T_{max} differed. This may be due to the fact that the required cumulative temperature threshold for initiating green-up varies among the different vegetation types (Hunter and Lechowicz, 1992; Diekmann, 1996; Piao et al., 2006a, b; Boschetti et al., 2009; Shen et al., 2011; Clark et al., 2014; Fu et al., 2014b; Liu et al., 2014; Nagai et al., 2015). In addition, Zhang et al. (2007) suggested that heat requirements decrease in cooler regions (from 40 °N southwards), which was supported by Liu et al (2014) who found that heat requirements decrease with increasing elevations in the Tibetan Plateau grasslands where the latitude ranges from 25 to 40 °N. Therefore, further studies are still needed to understand the role of elevation in driving spatial patterns of SOS sensitivity to temperature change in the temperate grassland region of China.

In addition to the effects of temperature, we also found that the SOS showed a significant response to spring cumulative precipitation. Shen et al. (2015a, b, c) suggested a greater sensitivity of SOS to precipitation in more arid areas, as vegetation maximizes the benefits of water. Consistent with that argument, we found that precipitation sensitivity was the lowest for temperate meadow in relatively wet regions and was the greatest for the temperate desert steppe in dry regions. On average, an increase of 10 mm in spring precipitation would advance SOS by 2.1 days for temperate desert steppe, but only 0.6 days for temperate meadow. It is reported that the positive effect of precipitation on the growth of temperate grasslands in China strengthened with increasing precipitation, but increasing precipitation failed to facilitate plant growth when growing season precipitation was more than 200 mm (Piao et al., 2006a, b), a precipitation threshold for grassland growth previously proposed by Tucker et al. (1991). In this study, we found that the sensitivity of SOS to spring precipitation significantly decreased with increasing precipitation when spring precipitation was below about 70 mm, but became very small when spring precipitation was close to or exceeded 70 mm (Fig. 8). Therefore, it implies that 70 mm of spring precipitation may be the limit of the water-use capacity of China's temperate grasslands for triggering the green-up. However, further studies are still needed to investigate the exact mechanism by which water conditions influence the start of the growing season.

5. Conclusions

The start date of the vegetation growing season (SOS) across the temperate grasslands of China significantly advanced from 1982 to 2015. Warmer temperature in winter and spring generally led to advancing SOS, but the effects of daytime versus nighttime warming were asymmetric. Changes in the SOS were more strongly associated with T_{max} rather than T_{min} in winter, but were more controlled by T_{min} than

by T_{max} in spring. This finding shows for the first time that the impacts of seasonal $T_{\max}$ and $T_{\min}$ should be considered separately in the SOS modules of terrestrial ecosystem models for temperate grasslands. Although the three grassland vegetation types displayed similar sensitivities of the SOS to spring $T_{\min}$, the sensitivity to winter $T_{\max}$ differed obviously. It suggests that the vegetation types should also be considered in exploring the response of SOS over the temperate grasslands of China to temperatures, especially for nighttime temperatures. In addition to temperature in winter and spring, spring precipitation also affected the SOS of the temperate grasslands of China. The sensitivity of SOS to spring precipitation decreased with increasing precipitation, but became stable and very small when spring precipitation was close to or exceeded 70 mm, which suggests that 70 mm of spring precipitation may be the limit of the water-use capacity of temperate grasslands in China for triggering the spring green-up.

It should also be noted that there may exist some limitations in this study. The estimates of the SOS from satellite data may contain some uncertainties. First, a satellite data-based approach is highly dependent on the quality of remote sensing data. Second, each NDVI pixel could only roughly reflect the changes of vegetation within an 8 km × 8 km area. In addition, it is difficult to validate the calculated SOS results due to lack of in situ observing phenology data in current study. And accurate phenology datasets from in situ observations are needed to further verify the results presented here. Although this study focused on the unchanged temperate grasslands during the study period for the purpose of reducing the impacts of land-use change on SOS results, it cannot completely exclude the possible effects of human activities such as grazing. Further studies are still needed to investigate the possible effects of environmental changes other than temperature and precipitation, including human activities, on SOS in temperate grasslands of China.

Acknowledgements

The authors wish to express their gratitude to the National Natural Science Foundation of China (Grant No. 41601048), the National Key Research and Development Program of China (Grant No. 2017YFC0212303), and the Excellent Young Scientists Foundation of the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences (Grant No.Y7H7041001) for funding this work.

References

Badeck, F.W., Bondeau, A., Böttcher, K., et al., 2004. Responses of spring phenology to climate change. New. Phytol. 162, 295–309.
Boschetti, M., Stroppiana, D., Brivio, P.A., Bocchi, S., 2009. Multi-year monitoring of rice crop phenology through time series analysis of MODIS images. Int. J. Remote. Sens. 30, 4643–4662.
Cao, R., Chen, J., Shen, M., Tang, Y., 2015. An improved logistic method for detecting spring vegetation phenology in grasslands from MODIS EVI time-series data. Agric. For. Meteorol. 200, 9–20.
Carlson, T.N., Ripley, D.A., 1997. On the relation between NDVI, fractional vegetation cover, and leaf area index. Remote. Sens. Environ. 62, 241–252.
Chen, X., An, S., Inouye, D.W., Schwartz, M.D., 2015. Temperature and snowfall trigger alpine vegetation green-up on the world's roof. Glob. Chang. Biol. 21, 3635–3646.
Chinese Academy of Sciences, 2001. Vegetation Atlas of China. Science Press, Beijing.
Cong, N., Piao, S.L., Chen, A.P., et al., 2012. Spring vegetation green-up in China inferred from SPOT NDVI data: a multiple model analysis. Agric. For. Meteorol. 165, 104–113.
Clark, J.S., Salk, C., Melillo, J., Mohan, J., 2014. Tree phenology responses to winter chilling, spring warming, at north and south range limits. Funct. Ecol. 28, 1344–1355.
Cong, N., Wang, T., Nan, H.J., et al., 2013. Changes in satellite-derived spring vegetation green-up date and its linkage to climate in China from 1982 to 2010: a multimethod analysis. Glob. Change Biol. 19, 881–891.
Diekmann, M., 1996. Relationship between flowering phenology of perennial herbs and meteorological data in deciduous forests of Sweden. Can. J. Bot. 74, 528–537.
Ding, M.J., Li, L.H., Nie, Y., Chen, Q., Zhang, Y.L., 2016. Spatio-temporal variation of spring phenology in Tibetan Plateau and its linkage to climate change from 1982 to 2012. J. Mt. Sci. 13, 83–94.
Ding, M., Li, L., Zhang, Y., et al., 2015. Start of vegetation growing season on the Tibetan Plateau inferred from multiple methods based on GIMMS and SPOT NDVI data. J. Geogr. Sci. 25, 131–148.
Donnelly, A., Caffarra, A., O'Neill, B.F., 2011. A review of climate-driven mismatches between interdependent phenophases in terrestrial and aquatic ecosystems. Int. J. Biometeorol. 55, 805–817.
Donnelly, A., Salamin, N., Jones, M.B., 2006. Changes in tree phenology: an indicator of spring warming in Ireland? Biol. Environ. 49–56.
Donnelly, A., Yu, R., Caffarra, A., et al., 2017. Interspecific and interannual variation in the duration of spring phenophases in a northern mixed forest. Agric. For. Meteorol. 243, 55–67.
Donnelly, A., Yu, R., Liu, L., 2015. Trophic level responses differ as climate warms in Ireland. Int. J. Biometeorol. 59, 1007–1017.
Fischer, T., Gemmer, M., Liu, L., Su, B., 2011. Change-points in climate extremes in the Zhujiang River Basin, South China, 1961–2007. Clim. Change. 110, 783–799.
Fu, Y.H., Liu, Y., De Boeck, H.J., et al., 2016. Three times greater weight of daytime than of night-time temperature on leaf unfolding phenology in temperate trees. New. Phytol. 212, 590–597.
Fu, Y.H., Piao, S., Op de Beeck, M., et al., 2014a. Recent spring phenology shifts in western Central Europe based on multiscale observations. Global. Ecol. Biogeo. 23, 1255–1263.
Fu, Y.H., Piao, S., Vitasse, Y., et al., 2015a. Increased heat requirement for leaf flushing in temperate woody species over 1980–2012: effects of chilling, precipitation and insolation. Glob. Change Biol. 21, 2687–2697.
Fu, Y.H., Piao, S., Zhao, H., et al., 2014b. Unexpected role of winter precipitation in determining heat requirement for spring vegetation green-up at northern middle and high latitudes. Glob. Change Biol. 20, 3743–3755.
Fu, Y.H., Zhao, H., Piao, S., et al., 2015b. Declining global warming effects on the phenology of spring leaf unfolding. Nature 526, 104–107.
Garonna, I., Jong, R., Wit, A.J.W., Mücher, C.A., Schmid, B., Schaepman, M.E., 2014. Strong contribution of autumn phenology to changes in satellite-derived growing season length estimates across Europe (1982–2011). Glob. Change Biol. 20, 3457–3470.
Goovaerts, P., 1997. Geostatistics for Nature Resources Evaluation. Oxford University Press, New York.
Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens. Environ. 83, 195–213.
Hunter, A.F., Lechowicz, M.J., 1992. Predicting the timing of budburst in temperate trees. J. Appl. Ecol. 29, 597–604.
IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
Karlsen, S.R., Elvebakk, A., Høgda, K.A., Grydeland, T., 2014. Spatial and temporal variability in the onset of the growing season on Svalbard, Arctic Norway—measured by MODIS-NDVI satellite data. Remote. Sens. 6, 8088–8106.
Körner, C., Basler, D., 2010. Phenology under global warming. Science 327, 1461–1462.
Lee, R., Yu FF, Price K.P., Ellis, J., Shi, P.J., 2002. Evaluating vegetation phenological patterns in Inner Mongolia using NDVI time-series analysis. Int. J. Remote Sens. 23, 2505–2512.
Liang, L., Schwartz, M.D., Fei, S., 2011. Validating satellite phenology through intensive ground observation and landscape scaling in a mixed seasonal forest. Remote Sens. Environ. 115, 465–472165.
Liang, L., Schwartz, M.D., Wang, Z., et al., 2014. A crosscomparison of spatiotemporally enhanced springtime phenological measurements from satellites and ground in a northern U.S. mixed forest. IEEE. Trans. Geosci. Remote. 52, 7513–7752.
Liu, L., Liu, L., Liang, L., Donnelly, A., Park, I., Schwartz, M.D., 2014. Effects of elevation on spring phenological sensitivity to temperature in Tibetan Plateau grasslands. Chin. Sci. Bull. 59, 4856–4863.
Liu, L., Zhang, X., Donnelly, A., Liu, X., 2016a. Interannual variations in spring phenology and their response to climate change across the Tibetan Plateau from 1982 to 2013. Int. J. Biometeorol. 60, 1563–1575.
Liu, L., Zhang, X., Yu, Y., Guo, W., 2017. Real-time and short-term predictions of spring phenology in North America from VIIRS data. Remote. Sens. Environ. 194, 89–99.
Liu, Q., Fu, Y.H., Zhu, Z., et al., 2016b. Delayed autumn phenology in the Northern Hemisphere is related to change in both climate and spring phenology. Glob. Change Biol. 22, 3702–3711.
Luedeling, E., Guo, L., Dai, J., Leslie, C., Blanke, M.M., 2013. Differential responses of trees to temperature variation during the chilling and forcing phases. Agric. For. Meteorol. 181, 33–42.
Melaas, E.K., Richardson, A.D., Friedl, M.A., et al., 2013. Using FLUXNET data to improve models of springtime vegetation activity onset in forest ecosystems. Agric. For. Meteorol. 171, 46–56.
Nagai, S., Saitoh, T.M., Nasahara, K.N., Suzuki, R., 2015. Spatio-temporal distribution of the timing of start and end of growing season along vertical and horizontal gradients in Japan. Int. J. Biometeorol. 59, 47–54.
Peng, S., Piao, S., Ciais, P., et al., 2013. Asymmetric effects of daytime and night-time warming on Northern Hemisphere vegetation. Nature 501, 88–92.
Piao, S., Cui, M., Chen, A., Wang, X., Ciais, P., Liu, J., Tang, Y., 2011. Altitude and temperature dependence of change in the spring vegetation green-up date from 1982 to 2006 in the Qinghai-Xizang Plateau. Agric. For. Meteorol. 151, 1599–1608.
Piao, S., Tan, J., Chen, A., et al., 2015. Leaf onset in the northern hemisphere triggered by daytime temperature. Nat. Commun. 6, 6911.
Piao, S.L., Fang, J.Y., Zhou, L.M., Ciais, P., Zhu, B., 2006a. Variations in satellite-derived phenology in China's temperate vegetation. Glob. Change Biol. 12, 672–685.
Piao, S., Mohammat, A., Fang, J., Cai, Q., Feng, J., 2006b. NDVI-based increase in growth of temperate grasslands and its responses to climate changes in China. Global. Environ. Chang. 16, 340–348.
Piao, S., Friedlingstein, P., Ciais, P., Viovy, N., Demarty, J., 2007. Growing season

extension and its impact on terrestrial carbon cycle in the Northern Hemisphere over the past 2 decades. Global Biogeochem. Cycles 21 GB3018.
Richardson, A.D., Hollinger, D.Y., Dail, D.B., Lee, J.T., Munger, J.W., O'keefe, J., 2009. Influence of spring phenology on seasonal and annual carbon balance in two contrasting New England forests. Tree. Physiol. 29, 321–331.
Richardson, A.D., Keenan, T.F., Migliavacca, M., Ryu, Y., Sonnentag, O., Toomey, M., 2013. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. Agric. For. Meteorol. 169, 156–173.
Shen, M., Piao, S., Chen, X., et al., 2016a. Strong impacts of daily minimum temperature on the green-up date and summer greenness of the Tibetan Plateau. Glob. Change Biol. 22, 3057–3066.
Shen, M., Piao, S., Cong, N., Zhang, G., Jassens, I.A., 2015a. Precipitation impacts on vegetation spring phenology on the Tibetan Plateau. Glob. Change Biol. 21, 3647–3656.
Shen, M., Piao, S., Dorji, T., et al., 2015b. Plant phenological responses to climate change on the Tibetan Plateau: research status and challenges. Natl. Sci. Rev. 2, 454–467.
Shen, M., Piao, S., Jeong, S.J., et al., 2015c. Evaporative cooling over the Tibetan Plateau induced by vegetation growth. Proc. Natl. Acad. Sci. 112, 9299–9304.
Shen, M., Tang, Y., Chen, J., Zhu, X., Zheng, Y., 2011. Influences of temperature and precipitation before the growing season on spring phenology in grasslands of the central and eastern Qinghai-Tibetan Plateau. Agric. For. Meteorol. 151, 1711–1722.
Shen, M., Zhang, G., Cong, N., Wang, S., Kong, W., Piao, S., 2014b. Increasing altitudinal gradient of spring vegetation phenology during the last decade on the Qinghai–Tibetan Plateau. Agric. For. Meteorol. 189, 71–80.
Shen, X., Liu, B., Li, G., Wu, Z., Jin, Y., Yu, P., Zhou, D., 2014a. Spatiotemporal change of diurnal temperature range and its relationship with sunshine duration and precipitation in China. J. Geophys. Res. 119, 13163–13179.
Shen, X., Liu, B., Li, G., Yu, P., Zhou, D., 2016b. Impacts of grassland types and vegetation cover changes on surface air temperature in the regions of temperate grassland of China. Theor. App. Climato. 126, 141–150.
Shen, X., Liu, B., Lu, X., 2017. Effects of land use/land cover on diurnal temperature range in the temperate grassland region of China. Sci. Total. Environ. 575, 1211–1218.
Shen, X., Liu, B., Lu, X., 2018. Weak cooling of cold extremes vs. continued warming of hot extremes in China during the recent global surface warming hiatus. J. Geophys. Res. http://dx.doi.org/10.1002/2017JD027819.
Tucker, C.J., Dregne, H.E., Newcomb, W.W., 1991. Expansion and contraction of the Sahara Desert from 1980 to 1990. Science 253, 299–301.
Tucker, C.J., Jorge, E., Pinzon, M.E., et al., 2005. An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data. Int. J. Remote. Sens. 26, 4485–4498.
Verger, A., Filella, I., Baret, F., Peñuelas, J., 2016. Vegetation baseline phenology from kilometric global LAI satellite products. Remote. Sens. Enviro. 178, 1–14.
Vrieling, A., Skidmore, A.K., Wang, T., et al., 2017. Spatially detailed retrievals of spring phenology from single-season high-resolution image time series. Int. J. Appl. Earth Obs. 59, 19–30.
Wang, C., Guo, H., Zhang, L., Liu, S., Qiu, Y., Sun, Z., 2015. Assessing phenological change and climatic control of alpine grasslands in the Tibetan Plateau with MODIS time series. Int. J. Biometeorol. 59, 11–23.
Wang, X., Wang, T., Guo, H., et al., 2017a. Disentangling the mechanisms behind winter snow impact on vegetation activity in northern ecosystems. Glob. Change Biol. http://dx.doi.org/10.1111/gcb.13930.
Wang, X., Wang, T., Liu, D., Guo, H., Huang, H., Zhao, Y., 2017b. Moisture-induced greening of the South Asia over the past three decades. Glob. Change Biol. (2017), 1–11.
Wold, S., 1995. PLS for multivariate linear modeling. Chemom. Meth. Mol. Des. 2, 195–218.
Wold, S., Sjöström, M., Eriksson, L., 2001. PLS-regression: a basic tool of chemometrics. Chemom. Intell. Lab. 58, 109–130.
Wu, C., Hou, X., Peng, D., et al., 2016. Land surface phenology of China's temperate ecosystems over 1999–2013: spatial–temporal patterns, interaction effects, covariation with climate and implications for productivity. Agric. For. Meteorol. 216, 177–187.
Wu, X., Liu, H., 2013. Consistent shifts in spring vegetation green-up date across temperate biomes in China, 1982–2006. Glob. Change Biol. 19, 870–880.
Yang, B., He, M., Shishov, V., et al., 2017. New perspective on spring vegetation phenology and global climate change based on Tibetan Plateau tree-ring data. Proc. Natl. Acad. Sci. 114, 6966–6971.
Yang, Y., Guan, H., Shen, M., Liang, W., Jiang, L., 2015. Changes in autumn vegetation dormancy onset date and the climate controls across temperate ecosystems in China from 1982 to 2010. Glob. Change Biol. 21, 652–665.
Yu, H., Luedeling, E., Xu, J., 2010. Winter and spring warming result in delayed spring phenology on the Tibetan Plateau. Proc. Natl. Acad. Sci. 107, 22151–22156.
Yu, H., Xu, J., Okuto, E., Luedeling, E., 2012. Seasonal response of grasslands to climate change on the Tibetan Plateau. PLoS One 7, e49230.
Zeng, H., Jia, G., Epstein, H., 2011. Recent changes in phenology over the northern high latitudes detected from multi-satellite data. Environ. Res. Lett. 6, 045508.
Zhang, G., Zhang, Y., Dong, J., Xiao, X., 2013. Green-up dates in the Tibetan Plateau have continuously advanced from 1982 to 2011. Proc. Natl. Acad. Sci. 110, 4309–4314.
Zhang, W., Yi, Y., Kimball, J.S., Kim, Y., Song, K., 2015. Climatic controls on spring onset of the Tibetan Plateau grasslands from 1982 to 2008. Remote Sens. 7, 16607–16622.
Zhang, X., 2015. Reconstruction of a complete global time series of daily vegetation index trajectory from long-term AVHRR data. Remote. Sens. Environ. 156, 457–472.
Zhang, X., Friedl, M.A., Schaaf, C.B., Strahler, A.H., 2004. Climate controls on vegetation phenological patterns in northern mid-and high latitudes inferred from MODIS data. Glob. Change Biol. 10, 1133–1145.
Zhang, X.Y., Tarpley, D., Sullivan, J.T., 2007. Diverse responses of vegetation phenology to a warming climate. Geophys. Res. Lett. 34, L19405.
Zhou, H.K., Yao, B.Q., Xu, W.X., et al., 2014. Field evidence for earlier leaf-out dates in alpine grassland on the eastern Tibetan Plateau from 1990 to 2006. Biol. Lett. 10, 20140291.
Zhu, W., Zhang, D., Jiang, N., Zheng, Z., 2017. Spatiotemporal variations of the start of thermal growing season for grassland on the Qinghai-Tibetan Plateau during 1961–2014. Int. J. Biometeorol. 1–9.